EOSC 112: Lecture Summary: Wednesday, September 12

Text Coverage: Chapter 3 pp. 41-43 and p. 47 – Planetary energy balance – including the greenhouse effect

**Announce**: There are now two new pages under the Special Topics web page. The first is the compilation of climate-related news articles, (click here). The second is an editorial debate about the Kyoto Protocol and the recent US National Academy of Sciences Report (click here).

- We derived three central quantities in the last lecture:
  - **The solar luminosity,** $L_{sun}$ ($\mathrm{W\,m^{-2}}$): In words – the power (W) leaving the surface of the sun. The current value is about $3.89 \times 10^{26}$ W – it changes by about 0.1% during the 11 year sunspot cycle (see page 241 of text). In the distance past, however, it was about 30% less than its current value.
  - **The solar constant,** $S$, ($\mathrm{W\,m^{-2}}$): In words – the flux ($\mathrm{W\,m^{-2}}$) received at the top of the atmosphere of a a point on a planet, when the sun is directly overhead. $S$ varies as the square of the distance between the sun and the planet, because $S$ is found by taking the luminosity and spreading it over a sphere with radius equal to the orbit of the planet. $S$ varies because the orbital shape and the tilt of earth's axis changes with time (p. 219, Figure 11-9).
  - **Globally averaged net insolation,** $S_{avg}$, ($\mathrm{W\,m^{-2}}$): In words – the shortwave radiative flux absorbed by the surface and atmosphere, averaged over the entire planet and over a time span much longer than a day. It depends on $S$ and on the *planetary albedo*, $A$. On a planet in which energy is easily transported by ocean and atmosphere, $S_{avg}$ can give a reasonable estimate of the energy absorbed by a $\mathrm{m^2}$ column of the planet.
- The only way for a planet to shed this absorbed $S_{avg}$ is by emitting thermal ($\lambda > 3\ \mu$m) photons to space. If it emits too few photons it will heat up, too many and it will cool down. Eventually the average temperature of the planet will settle down to its *effective radiative temperature*, $T_e$, for with the incoming shortwave and the outgoing longwave fluxes are in balance (on average):

$$S_{avg} = \sigma T_e^4 \tag{1}$$

or:

$$T_e = (S_{avg})^{1/4} \tag{2}$$

- Some points about Equation (2):
  - Because of the 1/4 power, it takes a fairly large change in $S_{avg}$ to produce a big change in $T_e$ via Equation (2). For example, if $S_{avg}$ increases by 20%, $T_e$ will increase by only $(1.2)^{1/4} \approx 1.05$.
  - **But ....** we haven't considered the possibility that $S_{avg}$ depends on $T_e$. If that is the case (and it definitely is for earth), then the final $T_e$ could be larger (positive feedback) or smaller (negative feedback) than the initial $T_e$ we calculate.

  - As we see this week in the lab, Equation (2) doesn't do a great job at predicting the observed surface temperature for many of the planets. In particular, when we put in our best current estimate for $S_{avg}$ for the Earth (240 $\mathrm{W\,m^{-2}}$), we get $T_e = 255$ K (-18 °C). Why is this value so much lower than the observed globally averaged surface temperature of 288 K (15 °C)?

- What is missing (at least for the Earth) from Equation (2) is the extra longwave flux that is supplied to the surface from the atmosphere. The simplest addition we can make to our energy balance model is to add one more layer – a black (in the longwave) atmosphere that absorbs all photons from the surface and reemits them to space. Although it's *black* in the longwave (completely absorbing) it's *transparent* in the shortwave (completely transmitting).

- In this new model (text Figure 3-2, p. 43) we still need to balance incoming $S_{avg}$ at the top of the atmosphere with the outgoing longwave flux. Thus the balance for the atmosphere looks like:

$$S_{avg} = \sigma T_{atm}^4 \tag{3}$$

  But now underneath the atmosphere the surface is free to heat up to a higher temperature, which is in balance with the incoming shortwave flux and the longwave flux from the atmosphere:

$$S_{avg} + \sigma T_{atm}^4 = \sigma T_{sfc}^4 \tag{4}$$

  Using Equation (1) we can rewrite this in steps as:

$$\begin{aligned} S_{avg} + S_{avg} &= \sigma T_{sfc}^4 \\ \sigma T_{sfc}^4 &= 2 S_{avg} \\ T_{sfc} &= \left(\frac{2 S_{avg}}{\sigma}\right)^{1/4} \\ T_{sfc} &= 2^{1/4}\left(\frac{S_{avg}}{\sigma}\right)^{1/4} \\ T_{sfc} &= 2^{1/4} T_e \end{aligned} \tag{5}$$

- Since $2^{1/4} \approx 1.19$ the result is that if $T_e = 255$ K (i.e. $S_{avg} = 240$ $\mathrm{W\,m^{-2}}$) Then $T_{sfc} = 1.19 \times 255$ K $= 303.5$ K. So now we're too high compared to 288 K by about 15.5 K.

- Why is the surface too hot? Actually, the atmosphere isn't completely absorbing for longwave (thermal) photons – it absorbs about 80% and transmits about 20%.

- How is it possible for the atmosphere to be (almost) transparent in the shortwave and nearly opaque in the longwave? Figure 3-12 shows that certain molecules, $H_2O$, $CO_2$ and many others, have an appetite for photons of very particular wavelengths. For example, as Figure 3-13 shows, $CO_2$ absorbs very strongly at wavelengths of 15 $\mu$m, 3 $\mu$m and 4.5 $\mu$m. In between each of these absorption "bands" are "windows" where photons can escape to space. Each of the absorption bands is associated with a different type of twisting or bending motion.

Oxygen ($O_2$) and nitrogen ($N_2$), with their simpler structure, don't interact with photons in the same way (see p. 48, Figure 3-15), and so are transparent to longwave radiation. (But $O_2$ does absorb very short-wavelength ultraviolet photons, breaking apart into single oxygen atoms).

- Click here to see a different view of the absorption bands, overlayed with the Planck functions for solar and terrestrial radiation. This figure shows why the 15 $\mu$m $CO_2$ absorption band is so important: it is placed near the maximum for terrestrial emission, and so "filling in" the 10 $\mu$m "window" by increasing $CO_2$ concentration produces a large reduction in the emitted radiation.

- Click here to see examples of the absorption behavior of many natural and man-made molecules. Note that many of them absorbed at wavelengths close to the 10 $\mu$m emission maximum.

- Click here to see an estimate of how big an effect each of these gasses has on changing the surface temperature of the Earth. (Note that $H_2O$, which is the most important greenhouse gas after $CO_2$, is missing from the figure, because its concentration depends on surface temperature).